LNG LIQUEFACTION –
"UNCOMMON KNOWLEDGE" LEADS TO INNOVATION

William P. Schmidt
Technology Manager, LNG Process Engineering
Matthew C. Holstine
Senior Process Engineer
Air Products and Chemicals, Inc.
Allentown, Pennsylvania, USA
schmidwp@airproducts.com

ABSTRACT

The LNG industry is rapidly changing: Floating LNG (FLNG), ultra lean feeds from shale/coal gas, larger single train sizes, cold climate locations, new process configurations, and new machinery types. The liquefaction unit must be adapted to meet these needs.

However, the LNG industry must manage risk while innovating, which requires carefully extending new technology from a known position; much innovation is based on some shared "common knowledge". This paper carefully analyzes past experience to show that some of this "common knowledge" or its extrapolation is incorrect. The implications of this analysis are discussed: more innovative designs with less technical risk, while staying near well-referenced equipment and processes.

This paper presents specific topics in the liquefaction unit's three main areas: process cycles, machinery, and heat exchange. Six points of the industry's "common knowledge" are explored and explained, with the new "uncommon knowledge" presented.

INTRODUCTION

The LNG industry continues to change, with new and growing sources and customers. This presents new challenges and requires new solutions. However, doing new things creates potential risks that the project may not perform as planned. Some risks are commercial, some are technical and some arise from project execution.

Risk can be reduced by building upon past experience. Past experience has much to teach. The challenge is to convert "lessons taught" by experience into "lessons learned", so that past experience influences future behavior or choices. Reviewing and building on lessons learned helps to ensure that the same issues do not occur again. Over time, these lessons get passed on as "common knowledge"; ideas that are accepted at face value, without requiring justification.

It is very helpful to capture this knowledge in simple statements. However, simplicity can be dangerous. The simple statement can be used in a situation where it doesn't apply, or the conclusions are too general for all situations. This misuse ignores Albert Einstein's guidance:

> "Make things as simple as possible, *but not simpler*."

In other cases, the incorrect conclusion was drawn originally. Unfortunately, if the statement gets repeated, it becomes common knowledge—even though it is incorrect—and this can create large problems:

> It isn't what you don't know that gets you into trouble. It's what you know for sure that just isn't so that is the problem.
> - paraphrased from Josh Billings (American author)

Developing an LNG liquefaction facility requires making many decisions. Properly making these decisions is critical for the technical and commercial success of the project (Schmidt 2010). Good design methodology identifies and manages technical risks. This paper presents six statements of "common knowledge" encountered by the authors in recent years. The background of each is presented and relevant data is analyzed to reveal new "uncommon knowledge". The correct "uncommon knowledge" gives the power to make correct decisions, which reduces or eliminates risk, ultimately providing better performing and more economical LNG liquefaction facilities.

BACKGROUND

Figure 1 below is a block flow diagram of a typical LNG facility.

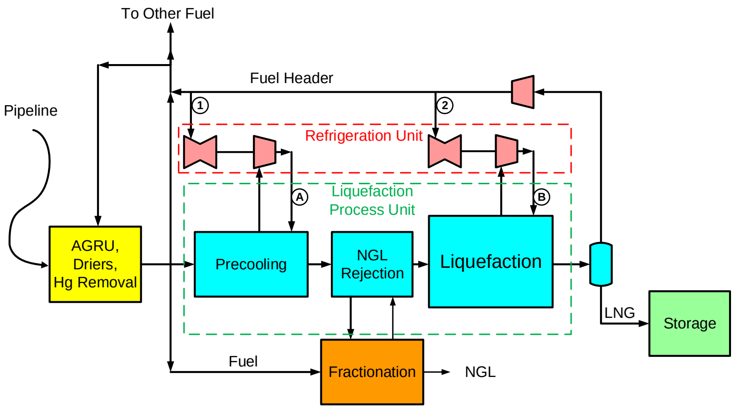


Figure 1 –LNG Facility Block Diagram

This paper uses the following definitions:

- LNG Facility – all units necessary to purify, liquefy and store LNG. It includes the units for Acid Gas Removal (AGRU), dehydration, mercury removal, liquefaction, end flash, storage, utilities, and all other necessary units.
- Liquefaction Unit – the process and equipment that convert purified natural gas from vapor to LNG, including Precooling, NGL (Natural Gas Liquids) Rejection and Liquefaction. The Main Cryogenic Heat Exchanger (MCHE) is the most significant equipment item, but this unit also contains piping, valves, and other equipment.
- Refrigeration Unit – the rotating equipment to compress the refrigerant used by the liquefaction unit; primarily the refrigeration compressors, their drivers, and other supporting equipment.

COMMON KNOWLEDGE #1: "LIQUEFYING PIPELINE GAS IS INEXPENSIVE AND SIMPLE."

The vast majority of existing baseload liquefaction plants are in remote locations with a dedicated feed gas source. In the past few years, new opportunities have arisen to liquefy natural gas in more developed areas with significant infrastructure. The feed source is a utility pipeline, which sends natural gas to residences (for heating or cooking), industries (for fuel) or chemical plants (for feedstock). This paper will refer to the first type as a "dedicated feed" and the latter as a "utility pipeline".

The "common knowledge" is that because utility pipeline gas is suitable for residential or commercial uses, it is suitable for liquefaction with minimal pretreatment and simple LNG facility designs. Unfortunately, this is incorrect. Utility pipelines typically have four major specifications: Heating Value (HHV), Wobbe index, Hydrocarbon (HC) Dew Point and water content. Liquefaction adds additional requirements for operation and safety:

- Nitrogen content – N_2 must be < 1% to prevent LNG rollover in the storage tank
- Freezing components removal – as the natural gas is cooled and liquefied, to prevent plugging downstream users or equipment by precipitation, the concentration of the following components must be limited: CO_2, BTX (Benzene, Toluene, Xylene) aromatics, higher boiling alkanes and alkenes (in particular C_6^+ components) and sulfur compounds. In addition, the maximum water concentration is at least an order of magnitude lower than required by a typical utility pipeline.
- Mercury Removal – to prevent aluminum corrosion or embrittlement.

Liquefying utility pipeline feedstock has three potential problems when compared to conventional baseload facilities:

I. Typical utility pipeline gas specifications do not ensure successful liquefaction operation.
II. The controlling design conditions may not occur at the extreme compositions.
III. The pipeline composition may vary significantly in the future.

These problems can make past design practices inadequate to ensure successful liquefaction. A case study illustrates these issues (see Table 1). An LNG export facility is being considered to liquefy and export natural gas from a North American utility pipeline. Table 1 shows three design compositions: Rich, Intermediate and Lean. It also shows the natural gas pipeline specifications, which include the pipeline pressure, % N_2, HHV, and HC Dewpoint. In addition, this pipeline operator provides the concentration of C_6^+ components . Note that all three feeds meet the pipeline specifications. Typically, this is the only information available to the liquefaction design team.

Table 1 – Case Study: Utility Pipeline Feed

	Typical utility P/L specification	Rich Feed	Intermediate Feed	Lean Feed
Min Pressure barg	N/A	45	45	45
N_2 Concentration	< 2-4%	1.0%	1.0%	1.0%
HHV BTU/SCF	950-1100	1031	1011	1007
Mj/nm^3	38.1 – 44.2	41.4	40.6	40.4
HC Dew Point °C	< - 7°	-46.4°	-32.1°	-81.3°
Meets Utility P/L Specification		✓	✓	✓

Table 2 provides the composition of each case, which is unknown to the liquefaction design team. For the Lean Feed, the potential precipitating components' concentrations (benzene, n-C_6 and n-C_8) are low enough to meet the additional requirements to liquefy natural gas.

Table 2 – Feed Composition Breakdown

	Rich Feed	Intermediate Feed	Lean Feed
Composition:			
C1	95.5%	97.8%	98.2%
C2	3.0%	1.0%	0.7%
C3	0.5%	0.2%	0.1%
C_6^+:	120 ppm	52 ppm	52 ppm
n-C6	100 ppm	0 ppm	51.4 ppm
n-C8	10 ppm	50 ppm	0.1 ppm
Benzene	10 ppm	2 ppm	0.5 ppm
Potential precipitation	**YES**	**YES**	**NO**
Viable Scrub Column or NGL unit	**YES**	**NO**	**NO**

The Rich Feed cannot be liquefied as-is, because benzene and octane will precipitate. However, the pressure is below critical and there is sufficient C_2-C_4 to operate a scrub column, which can remove the precipitating components prior to liquefaction. This is an example of the Type I problem, because the design team does not have sufficient information to identify that precipitation will occur. A technical solution exists—but this only helpful if the design includes one.

The intermediate feed contains insufficient C_2-C_4 to operate a scrub column or economically install an NGL extraction unit. However, the C_6^+ breakdown is such that the n-C_8 and benzene will precipitate and plug the liquefaction equipment in just a few hours of operation, so their removal is necessary. This is a Type II problem: even though the all conditions are between the extremes, because the components interact, this composition cannot be economically liquefied with conventional technology. ***This is in spite of the fact that the intermediate feed meets ALL of the utility pipeline specifications.***

The Type III potential issue is that the composition of the pipeline will vary over time. That is, even if today's composition was known and all current feeds are able to be liquefied, the future composition is unknown and may differ significantly from today. The feed sources and customer withdrawals change, both daily and seasonally.

Unfortunately, these examples are not hypothetical. There are instances in the LNG industry where plants supplied from a utility pipeline were unable to run because the actual feed differed from the design basis. Expensive and time consuming retrofits were required before full production could be achieved, sometimes taking months to implement. (Simonetti 2015)

Therefore, to address these risks, LNG liquefaction units fed from a utility pipeline must be designed to meet the additional requirements imposed by liquefaction. In addition, the unit must be robust and flexible to handle a wide range of feed compositions. A detailed discussion of the consideration and options to successfully design liquefiers fed from utility pipelines are beyond the scope of this paper; see (C. M. Ott 2012) (Chen 2013).

So the new "uncommon knowledge" is

"Natural gas from a utility pipeline cannot be considered clean and its composition will vary over time, so downstream LNG liquefaction units must be robust and flexible."

COMMON KNOWLEDGE #2: "IT'S BEST TO USE REFERENCED COMBINATIONS OF LIQUEFACTION PROCESSES AND DRIVERS"

Key steps in LNG project development are selecting the liquefaction process, the type and number of refrigerant compressor drivers and then matching the drivers to the required compressor loads. These decisions play a large role in setting the project CAPEX, operability, maintenance strategy, and energy consumption. To minimize the technical risk, it can be tempting to look at past experience, and only consider referenced combinations of the processes and driver. However, this can result in building a suboptimal facility, because it is rare that two facilities have the same project requirements.

A more effective methodology is to separately consider each of the main components, ensuring that each is adequately referenced and only then consider their interaction. A thorough risk analysis will identify the relevant experience and address all of the potential issues.

Because there are only a few liquefaction processes and driver types, it is not difficult to relatively quickly develop all possible process/driver configurations. (Krishnamurthy 2015) This screening identifies several potential configurations, with the approximate power, compressor configuration and the important advantages and disadvantages of each.

For each potential configuration, the individual references are relatively easy to obtain and compare to the planned project. However, it is more difficult to identify the interactions; some important ones are listed below:

- The drivers are available in only a few discrete sizes. This may cause the actual production to differ from the target production, especially when not using helper motors.
- The process compressor loads must be matched with individual drivers to consume the installed power. To use all or most of the installed power, carefully match the supply and demand.
- If more than one compressor is connected to a driver, then the two compressors must run simultaneously at all times.
- Different driver options are typically designed with an optimum or even fixed shaft speed. There is often an optimal shaft speed for the refrigerant compressor aerodynamics and efficiency. It is prudent to select a driver/compressor combination such that the optimal compressor and driver speeds are reasonably close.
- If parallel driver/compressor strings are used, consider how the strings interact, including

- Startup, where inlet/outlet pressures and temperatures must be matched as an offline compressor is returned to service.
- Normal operation (e.g., how to balance flow between the two strings).
- Shutdown, where special care must be taken to ensure that if one string experiences an unexpected shutdown, it does not cause a sympathetic trip of the other string. (Okasinski 2010)

Using the Air Products AP-C3MR™ LNG Liquefaction Process as a case study shows that all of these issue have been successfully addressed (C. M. Ott 2015). There are four compressor loads in the AP-C3MR process, and Table 3 below shows how the total power is typically consumed:

Table 3 – Power Consumption by Compressor Service

	Power consumption (% total)
Propane	30-40%
Low Pressure Mixed Refrigerant (LP MR)	30-40%
Medium Pressure MR (MP MR)	13-20%
High Pressure MR (HP MR)	13-20%

Table 4 – Some Driver and Compressor Combinations for C3MR Process

Drivers	Driver Power Split	Driver/compressor match: Driver	Driver/compressor match: Compressor(s) on the String	Comments
2	2 x 50%	#1	C3 + HP MR	Operating (SplitMR® Machinery Configuration)
		#2	LPMR + MP MR	
2	2 x 50%	#1 & #2	C3 + LPMR + HP MR (50%)	In construction (Bocherel 2016)
2	33% / 67%	#1	C3	Operating
		#2	LPMR + MPMR + HPMR	
3	3 x 33.3%	#1	C3	Operating w/ Gas Turbines In construction w/ electric motors (Mallett 2013)
		#2	LPMR	
		#3	MPMR + HPMR	
4	4 x 25%	#1, 2	C3 + HP MR (50%)	Developed in several FEEDs (Parallel SplitMR®)
		#3, 4	LPMR + MP MR (50%)	
5	5 x 20%	#1 & #2	C3	Operating (Bergeron 2015)
		#3, 4, 5	LPMR + MPMR + HPMR	

Note: This table is not all-inclusive; other driver/compressor configurations are in operation and many more have been examined through studies and FEEDs.

The actual power consumed by each stage varies within the range above, depending on the project specifics. The process design can vary the power split between compressors to some extent, optimizing the match between the compressors and drivers. A typical power split of 33%/33%/17%/17% for C3/LPMR/MPMR/HPMR can be matched well with 2, 3, 4 and 5 drivers. Table 4 above shows how this has been done for past projects, each with specific needs. For the early baseload LNG plants, steam turbines were the preferred driver; they have subsequently been displaced by industrial gas turbines. In the past decade, higher efficiency aeroderivative gas turbines have become accepted in the LNG industry, and the C3MR process is operating successfully with these at Papua New Guinea (Bergeron 2015). Finally, electric motors are being used in areas with a strong electric infrastructure; an electric motor C3MR plant is in construction (Mallett 2013). This experience shows that the AP-C3MR™ LNG Liquefaction Process is very adaptable. It can be optimized to match nearly any combination of driver size and compressors.

So the new "uncommon knowledge" is

"New combinations of LNG liquefaction processes, compressors and compressor drivers can be successfully implemented by building upon past individual experiences."

COMMON KNOWLEDGE #3: "AUTOCONSUMPTION IS THE BEST WAY TO COMPARE LIQUEFACTION PROCESS EFFICIENCY"

A key economic parameter in any LNG facility is "autoconsumption", which is the feedgas consumed to remove impurities and convert natural gas into liquid. Autoconsumption is the portion of the feed which does not end up in the LNG or NGL product; it is the amount of feed consumed to provide thermal or mechanical energy, or is lost as part of the processing. Autoconsumption is significant; typically, it is 4 to 12% of the natural gas feed for baseload LNG plants.

The primary autoconsumption loss is to fuel, and the majority of fuel is consumed to power the refrigeration compressor drivers (streams 1 and 2 in Figure 1). "Autoconsumption" is a common measure of the overall efficiency of the LNG ***facility***.

"Specific power" measures how much refrigeration energy is needed to convert feed natural gas into LNG. Another way to think of this is how effectively the process uses the refrigeration energy contained in streams A and B (shown in Figure 1) to make LNG. Specific power is a good way to compare the efficiency difference between liquefaction ***processes***, with a more efficient process having lower specific power.

Reducing autoconsumption is one way to improve project economics; doing so increases production without increasing pipeline feed rate. Because the refrigeration drivers make up over 70% of the autoconsumption, it is natural to focus on them to reduce plant fuel consumption. Possible ways to reduce the turbine fuel consumption are to reduce the liquefaction process power requirement (i.e., specific power) or to reduce the turbine heat rate (which reduce the fuel flow at points 1 and 2, while maintaining the refrigerant flow conditions at points A and B in Figure 1). Table 5 compares liquefaction process power consumption and Table 6 compares the heat rate of different gas turbine drivers.

Because there are several efficiency measures (e.g. autoconsumption, Liquefier Process specific power and gas turbine heat rate), it is important be consistent when making efficiency comparisons. A case study illustrates this point. A project is considering which process to select, C3MR or SMR, and is also considering whether to use industrial or aeroderivative gas turbines. A key factor in the design is efficiency. Table 5 shows that SMR's specific power is 15% higher than the C3MR process and Table 6 shows that aeroderivative gas turbines consume about 20% less fuel than industrial turbines, for the same power output. Table 7 below shows the relative autoconsumption for the various combinations of process and driver autoconsumption.

Table 5 – Liquefaction Process Comparison Comparison

Cycle	Relative specific power (1)
C3MR	1.0
DMR	1.0
Cascade	1.1
SMR	1.15-1.25
N2	1.3-2.0

Note: (1) liquefaction process specific power typically uses units of "kWh/tonne LNG". A lower specific power indicates a higher process efficiency

Table 6 – Gas Turbine Driver

Turbine Type	Relative Heat Rate (1)
Aeroderivative Gas Turbine	0.6
Industrial Gas Turbine	0.8
Steam	1.0

Note: (1) Heat rate quantifies how effectively the gas turbine converts the fuel heat into shaft power to drive the compressors. Units for heat rate are BTU/hp-hr or kJ/kWh. A lower heat rate is a more efficient gas turbine.

Table 7 – Relative Driver Autoconsumption (1)

Gas Turbine	C3MR	SMR
Industrial	1.00	1.15
Aero	0.83	0.96

Note: (1) Autoconsumption = Driver heat rate x specific power

Note that the driver type is selected independently from the liquefaction process. Therefore the lowest auto-consumption is obtained by choosing the most efficient driver type (aero-derivative) and the more efficient liquefaction process (C3MR). The SMR process with industrial gas turbines has the highest autoconsumption; C3MR with aeroderivatives has the lowest. However, it is not valid to compare the SMR process with aeroderivatives (0.96) with C3MR and industrial gas turbines (1.00), and conclude that SMR is a more efficient process. This can easily happen when obtaining data from different sources, which use different definitions of "efficiency".

The key lesson from this example is to be careful to compare processes on a similar basis. Do not mask efficiency losses in the liquefaction process with efficiency gains in the gas turbines. This leads to some new "uncommon knowledge":

"Compare the efficiency of LNG liquefaction FACILITIES with autoconsumption; Compare the efficiency of LNG liquefaction PROCESSES with specific power.

COMMON KNOWLEDGE #4: "LNG LIQUEFACTION HEAT EXCHANGERS DO NOT OPERATE STABLY AT LOW RATES"

In the mixed refrigerant process, the hot and cold streams both are two phase. The feed natural gas starts as a vapor, condenses, and becomes a liquid. The mixed refrigerant starts as a liquid and boils as it absorbs the heat from the natural gas. As the fluids boil and condense, both vapor and liquid are present.

For an LNG facility, liquefaction occurs inside tubes (in the case of a coil-wound or other type of shell-and-tube heat exchanger) or in small passages (in the case of a brazed aluminum heat exchanger). When the fluid is moving downwards, gravity pulls the liquid along with the vapor. However, if the fluid is moving upwards, gravity's downward pull opposes the desired fluid motion. (See Figure 2). Upwards two-phase flow can be problematic if the vapor velocity is too low to carry the liquid upwards; the liquid will then separate and run backwards. If this occurs, eventually so much liquid accumulates that it surges forward. After the liquid is depleted, the liquid flow stops and the cycle repeats. This stop/start pulsing flow pattern creates process instabilities. The conditions that give stable flow can be predicted, and they depend on many factors, including overall velocity, liquid and vapor amounts, physical properties, and tube diameter.

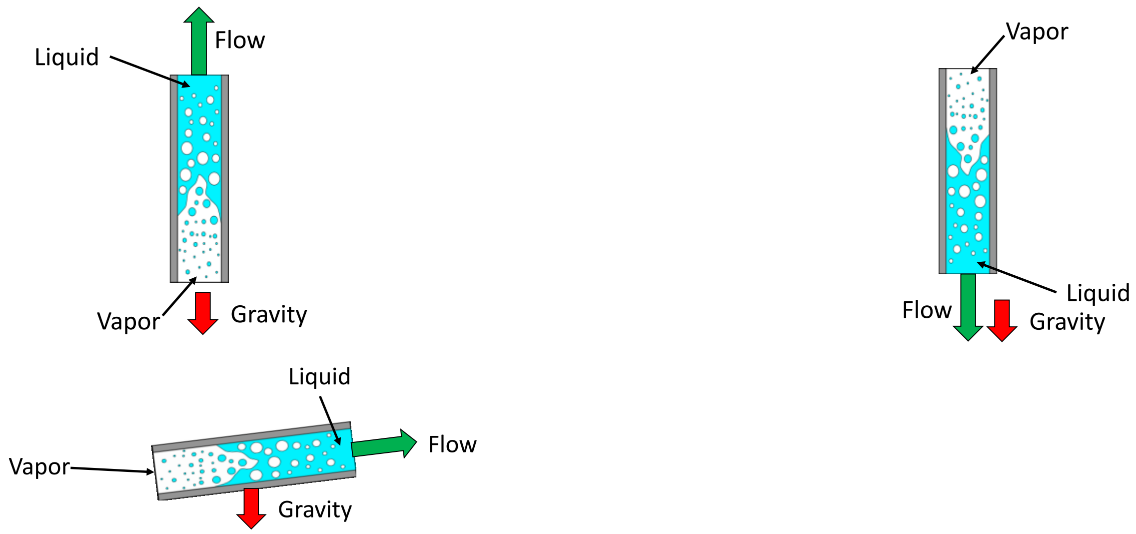
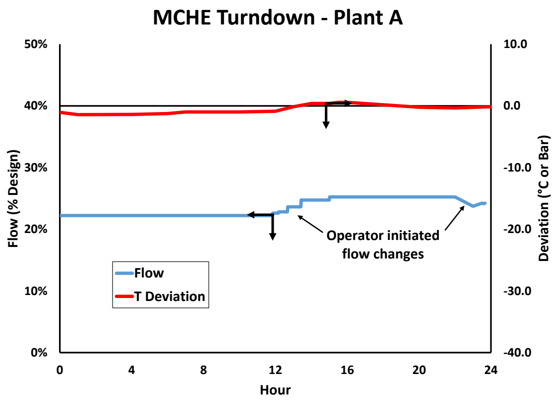


Figure 2 – (a) Upwards Flow b) Downwards Flow (c) CWHE Tubeside Flow

For horizontal flow, gravity is perpendicular to the flow direction. Gravity has a smaller effect and it is easier to maintain stable flow in the horizontal. In a Coil Wound Heat Exchanger (CWHE), the tubes are very close to horizontal, only slightly inclined. The flow pattern within the tubes is shown schematically in Figure 2 (c), making flow stability much easier to maintain in a CWHE. On the shellside of a CWHE, liquid flows downwards over the outside of the tubes. Gravity is moving the fluid in the desired direction, so the 2 phase flow is stable in virtually all conditions.

Flow stability has a very practical implication. Unstable flow can at turndown lead to unstable heat exchanger performance, with varying temperatures, flowrates and pressures, and may lead to potentially damaging thermal stresses. If the fluctuations are too large, the process will be difficult to operate and control, and in extreme cases, will damage the exchanger.



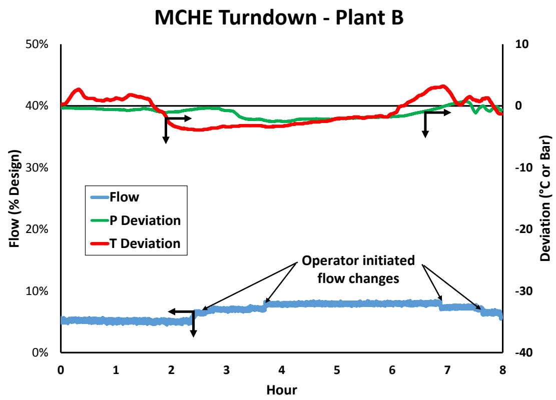


Figure 3 – Plant A Stable CWHE Turndown

Figure 4 – Plant B Stable CWHE Turndown

However, as discussed above, the CWHE configuration helps to stabilize both tube and shell side flows. Properly considering all important factors gives a robust design, leading to stable CWHE operation at low rates. (These include tubeside velocity, vapor quality, fluid physical properties, and the exchanger geometry.) Figures 3 and 4 show low rate operating data: the LNG flowrate as % of nameplate, the outlet LNG temperature around a target, and where available, the outlet LNG pressure. Figure 3 shows Plant A operating stably at 20 to 25% of design, with production curtailed by feed gas availability. Figure 4 shows Plant B with stable operation at 5% to 8% of design, during the initial cooling of the LNG storage tank. Even at these extremely low rates, the outlet pressure and temperature were stable for many hours, showing that stable operation is achieved.

This actual plant operating data conclusively shows that CWHEs can operate at very low rates. So the new "uncommon knowledge" is

"CHWEs are proven to operate stably at very low rates, even down to 5% of nameplate."

COMMON KNOWLEDGE #5: "MULTIPLE SMALL TRAINS PRODUCE MORE ANNUAL LNG AND ARE MORE RELIABLE THAN ONE LARGE TRAIN"

To advance beyond the common knowledge regarding parallel small trains, it is necessary to define terms that characterize on-stream performance:

- **Reliability** is the time between failures, typically expressed Mean Time Between Failure (MTBF). (Failure frequency is the reciprocal of reliability.) However, reliability provides no information on length of failure, so the impact on production cannot be directly determined; that requires the downtime duration after the failure.
- **Availability** is the percent of time that the component is available to do its function when required, which is set by the number and duration of outages. Availability can be for planned, unplanned or all outages.

This paper investigates how parallel configurations affect availability and annual production of an LNG facility due to *unplanned* outages. Although a detailed discussion of planned outages is beyond the scope of this paper, some considerations on planned outages are discussed later.

Installing two full size components (i.e., 2 x 100%) in parallel can increase availability by reducing the consequence if a single component becomes unavailable. However, it is typically impractical or prohibitively expensive to install parallel full size (100%) key equipment, such as refrigeration compressors or the MCHE. Instead, installing 2 x 50% components maintains 50% production in the event of a component failure, albeit with a CAPEX penalty. It is commonly believed that installing smaller, parallel components or units will increase the overall availability and annual LNG production. However, this is not always the case; to obtain the maximum benefit, strategically evaluation is necessary.

Parallel components come with a cost; typically parallel (2 x 50%) liquefaction trains are 35% to 40% more expensive than the single train (1 x 100%) (Durr 2005). In addition, 2 x 50% trains generally require a larger plot area. The extra CAPEX and plot space is much less if only key components (e.g., compressor strings) are installed as 2 x 50%, while using a single 100% liquefaction unit.

A case study examines the availability of four configurations of a liquefaction process and refrigeration units (see Figure 5 below). This case study uses typical component availabilities:

Single Driver/Compressor string = 99.2% (2 outages/yr @ 1.5 days/outage)
Liquefaction process = 99.7% (1 outage/yr @ 1 day/outage)

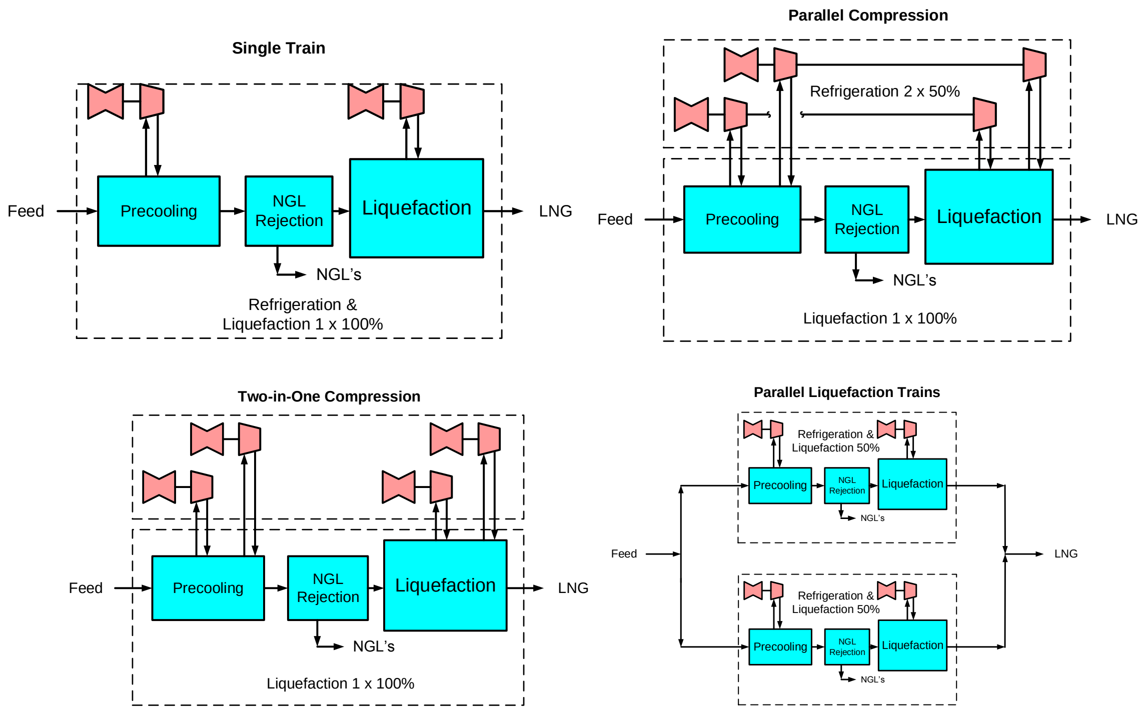


Figure 5 – LNG Liquefaction Configurations

For each configuration, Table 8 shows the unplanned outage availability, time at production capacity (i.e., 0%, 50% and 100% of nameplate) and the total average yearly production.

Table 8 – Availability Comparison: Unplanned Outages Only

Configuration	Single Train	Parallel Compression	Two-in-One Compression	Parallel Trains
Liquefaction Process	1 x 100%	1 x 100%	1 x 100%	2 x 50%
Refrig'n Compr Strings	1 x 100%	2 x 50%	4 x 25%	2 x 50%
% time producing:				
100% LNG	98.11%	98.11%	96.55%	96.23%
50% LNG	0.0%	1.59%	3.13%	3.73%
0% LNG	1.89%	0.30%	0.33%	0.04%
Total trips/yr (liquefier + Compressor)	5	5	9	10
Total annual production (% nameplate)	98.11%	98.90%	98.11%	98.11%
CAPEX (order of magnitude)	Base	Base + $10-50 MM	Base + $20-100 MM	Base + $500-2000MM

Table 8 shows that adding parallel components decreases the time when no LNG is being produced, but increases the time when production is only 50% of nameplate. These combine to decrease the total time at 100% production. Note also that as more components are added, the total number of trips increases. In addition to placing a burden on the operating staff, more frequent trips increase the probability of larger problems, because long term problems arise more often during atypical operating modes (e.g., startup and shutdown).

What may be surprising is that parallel compression (2 x 50%) configuration with a single liquefaction train produces the highest most LNG over an entire year. This configuration has two significant advantages: the minimum number of components (3, which minimizes the total number of trips) and parallel compression strings (so that a single compression trip maintains 50% production).

CAPEX is another key factor in availability analysis. The single train is the lowest cost. Adding parallel compressor strings adds millions of USD in CAPEX. Installing both parallel compression and liquefaction units adds hundreds of millions to billions of USD while reducing the time making 0% of nameplate to virtually nil, but does not increase the total annual production.

There are other factors which are not included in this simplified unplanned downtime analysis; including these factors will slightly alter the analysis for specific situations:

- For parallel compressor strings, if one trips offline, the restart time is usually faster because the liquefaction process continues to run, remaining at operating conditions. This will increase availability and the total annual production for this configuration. This also reduces the thermal cycles and stresses on the cryogenic equipment, which increases its reliability and availability.

- Parallel compression may potentially slightly increase the number of trips, because tripping one string can sympathetically trip the remaining string. Correct process control strategies will minimize or eliminate sympathetic trips. (Okasinski 2010)
- If feed gas is available, it is sometimes possible to operate the facility above 100% of nameplate to make up lost production. The parallel compression and total parallel configurations may be able to do this more readily, because when one string is offline, 100% feed gas is typically available to feed the nominal 50% units.
- When it is possible to perform planned maintenance on one parallel unit while the other is producing LNG (Simultaneous Maintenance and Operation or SIMMOP), planned maintenance outages will not identically affect the availability of different configurations. SIMMOP requires isolating the process side of the offline unit and making the surrounding area safe for maintenance activities, such as welding and crane operation. Whether SIMMOP is possible is particularly important when comparing industrial gas turbines (few outages, each lasting a few weeks) with aeroderivative gas turbines (more, but shorter, outages). If SIMMOP is possible, then during some of planned maintenance time, the production is 50%—not 0%—LNG production, increasing availability and annual production.

Which is the best configuration? With reference to Einstein, the answer can be simplified, but cannot be made too simple. Splitting 1 x 100% items into 2 x 50% parallel items:

- Parallel components decrease reliability, due to more unplanned trips.
- Parallel compression strings reduce the time producing 0% and 100% of nameplate, while increasing the time at 50%.
- Parallel compression strings typically maintains the total annual production, but redistributes the time at 0%, 50% and 100% production.
- Parallel compression reduces thermal stresses and cycles on cryogenic equipment.
- Carefully arranging parallel compression strings increases the total annual production.
- Parallel liquefaction units reduce the "no production" time to a very low number, but this is extremely capital intensive.

So the new "uncommon knowledge":

"Improving availability using 2 x 50% components is possible, but must be done carefully—otherwise there is little or no benefit from the higher CAPEX."

COMMON KNOWLEDGE #6: "TWO 50% TRAINS TURN DOWN BETTER THAN ONE 100% TRAIN"

With the developing spot market for LNG, there is increasing interest in constructing LNG capacity which is not dedicated to a take-or-pay contract or where the available feed flowrate varies with time. This commercial arrangement increases the probability that the LNG facility will not be fully loaded at all times, so it may run at turndown for extended periods of time. In these situations, it is desirable that the turndown also be efficient, i.e., that the liquefier specific power be constant or only slightly increase as the production is decreased.

- As was discussed earlier in this paper, LNG liquefaction processes using CWHEs can turn down to very low rates. Stable operation at 5% of nameplate has been demonstrated. The heat transfer efficiency is maintained—and sometimes improved—because excess heat transfer area is available.
- Distillation columns in the AGRU and fractionation unit (which remove potentially precipitating components) can be designed for high turndown.
- The centrifugal refrigeration compressors can typically reduce the inlet volumetric flowrate to 70 to 80% of the design point without recycle. Adjusting the MR composition maintains a nearly constant specific power at these flows. Below 70% production, some discharge flow must be recycled around the compressor to prevent surge, so the total compressor power consumption does not decrease further with lower LNG production.

If production below 50% of nameplate is desired for long periods of time, the power consumption can be significantly reduced by installing 2 x 50% compression strings. When producing less than 50% of nameplate, one string can be shutdown, eliminating its power consumption. Again, because CWHEs can run stably at much less than 50%, there is no need to split the liquefaction into 2 x 50% units. This can save significant CAPEX and plot space.

Figure 6 below shows typical power reduction at lower production rates for the C3MR process using 1 x 100% and 2 x 50% compression strings. As production decreases, adjusting MR composition lowers power consumption down until about 70% nameplate. Below that, the power consumption levels off. If 2 x 50% strings are installed, a further decrease occurs at approximately 50% nameplate. Essentially all of this decrese is due to shutting down one compressor string. *Note that there is no difference in power consumption between the two configurations until the production falls below 50% of nameplate*.

So the new "uncommon knowledge" is

"Above 50% production of nameplate, making components 2x50% saves minimal power. To increase power savings below 50% production, only the compression strings need to be 2 x 50%."

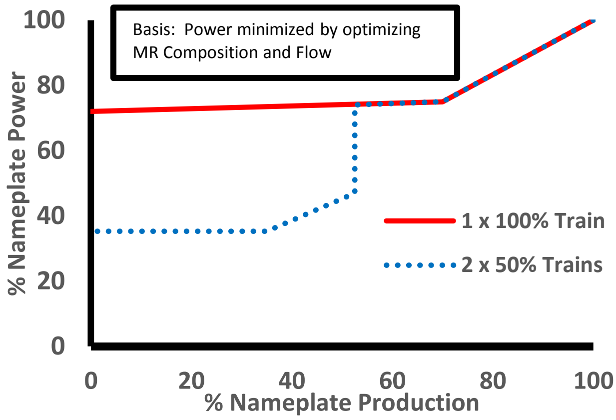


Figure 6 – LNG Liquefaction Turndown

SUMMARY AND CONCLUSIONS

This paper has shown much common knowledge contains the dangers warned of by Billings and Einstein. The common knowledge is either too simple, or even worse, it "just isn't so". Six common knowledge statements have been examined in detail, and new "uncommon knowledge" is shared with the reader. Following the new uncommon wisdom will result in lower costs or higher production—and sometimes both!

REFERENCES

Bergeron, David. "Papua New Guinea LNG Project – Development and Deployment of Novel Aeroderivative Gas Turbine / Refrigerant Compression Configuration to Achieve Efficiency, Flexibility, and Reliability." *Gastech.* Singapore, 2015.

Bocherel, Pascal, Jim Strohman,et al. "Converting Dominion Cove Point LNG into Bidirectional Facility." *LNG-18.* Perth, Australia, 2016.

Chen, Fei, Christopher M. Ott. "Lean Feed Gas Liquefaction - Challenges and Solutions." *LNG Journal*, Jan/Feb 2013.

Durr, Charles, David Coyle, Don Hill, Sharon Smith. "LNG Technology for the Commericially Minded." *Gastech.* Bilboa, Spain, 2005.

Krishnamurthy, Gowri, Mark J. Roberts, Joseph G. Wehrman. "Drive Your LNG Project to Success with Optimal Machinery Selections." *LNG Journal*, May 2015: 36-39.

Mallett, Mark, Chet Lloyd, John Dobler, Justin Capouch, Don Hill. "Freeport LNG Liquefaction Project." *LNG-17.* Houston, TX, 2013.

Okasinski, M.J and Yu Nan Liu. "Dynamic Simulation of C3-MR LNG Plants with Parallel Compression Strings." *LNG-16.* Oran, Algeria, 2010.

Ott, Christopher M., William Schmidt, Joseph Wehrman, John Dally. "Large LNG Trains: Technology Advances to Address Market Challenges." *Gastech.* Singapore, 2015.

Ott, Christopher M., Yu Nan Liu, Mark Roberts, Xukun Luo, Fei Chen. "Heavy Hydrocarbon Removal from Lean Feed Gas." *Gastech.* Amsterdam, 2012.

Schmidt, William P., Christopher M. Ott, Yu Nan Liu, William Kennington. "How the Right Technical Choices Lead To Commercial Success." *LNG-16.* Oman, Algeria, 2010.

Simonetti, Tania, Manikandan Narayanan, Christian Bladanet, Fei Chen, Christopher Ott. "Innovations in Small to Mid-Scale LNG Plants." *World Gas Conference.* Paris, France, 2015.